A bottom-up approach to a minimal EFT for leptogenesis, dark matter, and neutrino masses

Based on Eur. Phys. J. C 85, 801 (2025)

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DISCRETE 2026

November 13 - 17, 2026

Standard Model and the early Universe

$\Omega_{\Lambda,0} = (68.9 \pm 0.60)\%$ $\Omega_{c,0} = (26.0 \pm 0.36)\%$ $\Omega_{b,0} = (4.89 \pm 0.07)\%$

$\Omega_{\gamma,0} = 2.47 \times 10^{-5}/h^2$ $\Omega_{\nu,0} = \sum m_\nu/(93.12\ \text{eV})/h^2$ $h = 0.677 \pm 0.004$

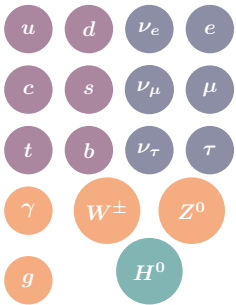
[Navas *et al.* 2024 (Particle Data Group)]

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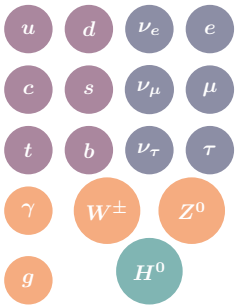
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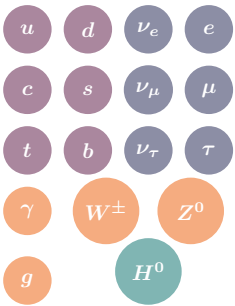


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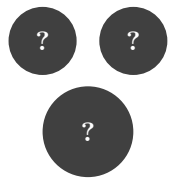
[Blažek, Maták, Ramaj, Sabová 2025]

Standard Model and the early Universe

$$\mathcal{L} = \mathcal{L}_{\mathsf{SM}} + \sum_{k=1}^{N} \frac{1}{\Lambda^{d_k-4}} \mathcal{C}_k \mathcal{O}_k$$



$+$



$=$

$$\begin{cases} \Omega_{c,0} \\ \Omega_{b,0} \\ m_\nu \end{cases}$$

$\Omega_{b,0}$ and $\Omega_{c,0}$ cogenesis

- Renormalizable models [Bento, Berezhiani 2001; Falkowski, Ruderman, Volansky 2011; ...]
  or effective field theories [Baldes, Bell, Petraki, Volkas 2014; Ciscar-Monsalvatje, Ibarra, Vandecasteele 2024; ...]

- Dark matter freeze-out [Davoudiasl, Morrissey, Sigurdson, Tulin 2010; Baldes, Bell, Petraki, Volkas 2014; ...]
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- Asymmetry generation through decays [Bhattacharya, Roshan, Sil, Vatsyayan 2022; Goudelis, Papachristou, Spanos 2022; ...] or scatterings [Bento, Berezhiani 2001; Goudelis, Karamitros, Papachristou, Spanos 2022; ...]

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What level of complexity in terms of particles and their interactions is necessary?
What can the minimal effective theory look like?

$\Omega_{b,0}$ and $\Omega_{c,0}$ cogenesis

- **Cold dark matter**: a stable massive particle coupled to the Standard Model fields via a portal operator

- **Baryon asymmetry**: $B - L$ number violation
  independent C and CP violation in particle reactions
  departure from thermal equilibrium

[Sakharov 1967]

CP asymmetries from interfering amplitudes

$$S = 1 + \mathrm{i}T \qquad \Delta|T_{fi}|^2 = |T_{fi}|^2 - |T_{\bar{f}\bar{i}}|^2 = |T_{fi}|^2 - |T_{if}|^2 \tag{1}$$

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$$\begin{aligned} T_{fi} &= C_{fi}^{\text{tree}} K_{fi}^{\text{tree}} + C_{fi}^{\text{loop}} K_{fi}^{\text{loop}} \\ T_{if} &= C_{if}{}^{\text{tree}} K_{if}^{\text{tree}} + C_{if}{}^{\text{loop}} K_{if}^{\text{loop}} \end{aligned} \quad \Longrightarrow \quad \Delta|T_{fi}|^2 = -4\,\mathrm{Im}[C_{fi}^{\text{tree}} C_{fi}^{*\text{loop}}]\,\mathrm{Im}[K_{fi}^{\text{tree}} K_{fi}^{*\text{loop}}] \tag{3}$$

Holomorphic cutting rules and CP asymmetries

$$S^\dagger S = 1 \qquad S = 1 + \mathrm{i}T \qquad \mathrm{i}T^\dagger = \mathrm{i}T - \mathrm{i}T\mathrm{i}T^\dagger \tag{4}$$

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[Coster, Stapp 1970; Bourjaily, Hannesdottir, *et al.* 2021]

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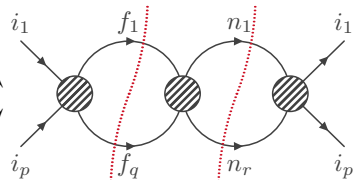
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Holomorphic cutting rules and *CP* asymmetries

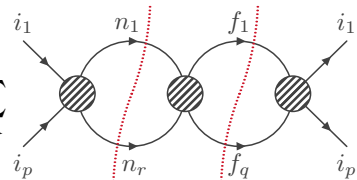
$$\Delta|T_{fi}|^2 = \sum_n \left(\mathrm{i}T_{in}\mathrm{i}T_{nf}\mathrm{i}T_{fi} - \mathrm{i}T_{if}\mathrm{i}T_{fn}\mathrm{i}T_{ni}\right) - \sum_{n,k} \left(\mathrm{i}T_{in}\mathrm{i}T_{nk}\mathrm{i}T_{kf}\mathrm{i}T_{fi} - \mathrm{i}T_{if}\mathrm{i}T_{fk}\mathrm{i}T_{kn}\mathrm{i}T_{ni}\right) + \dots \tag{7}$$

[Blažek, Maták 2021]

$$\int \prod_{l=1}^{q} [\mathrm{d}\mathbf{p}_{fl}]\, \Delta|T_{fi}|^2 = \sum_{\{n\}}$$



$$- \sum_{\{n\}}$$

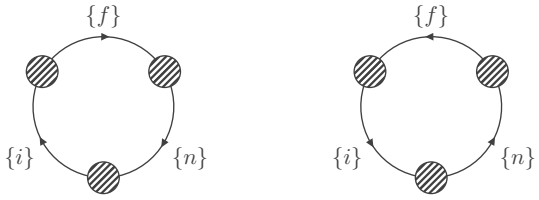


(8)

Holomorphic cutting rules and *CP* asymmetries

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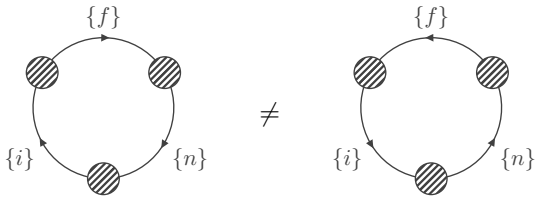
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[Covi, Roulet, Vissani 1998; Botella, Nebot, Vives 2006]

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- Imaginary kinematics from loop integrals
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or

- Forward scattering diagrams with at least two simultaneous on-shell cuts
- Combinations of couplings represented by vacuum diagrams that are *not* invariant under charged-particle arrow reversal

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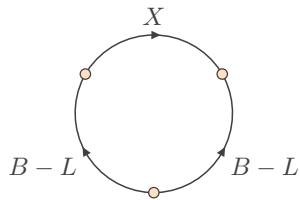
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$$\mathcal{L}_{\text{eff}} \supset \mathcal{O}_{B-L}\mathcal{O}_X,\ \mathcal{O}_{B-L}\mathcal{O}_X^c,\ \mathcal{O}_{B-L}^{\dagger 2}$$



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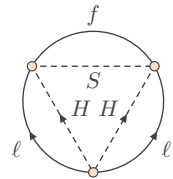
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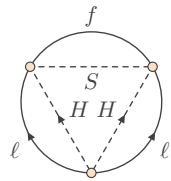
$$\mathcal{L}_{\text{eff}} = \frac{\lambda}{\Lambda} S \bar{f} P_L \ell H + \frac{\lambda'}{\Lambda} H \bar{\ell^c} P_L \ell H + \text{h.c.} \tag{9}$$

[Blažek, Maták, Ramaj, Sabová 2025]



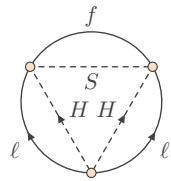
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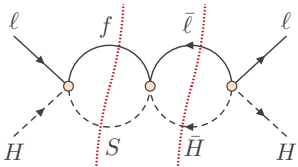
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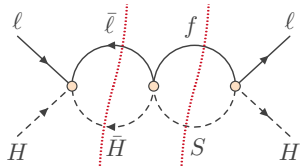


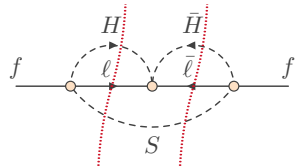
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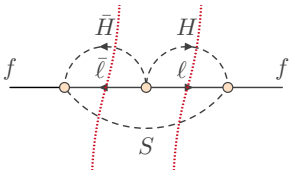
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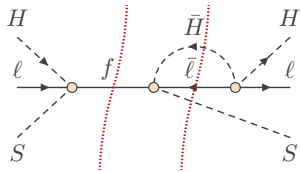


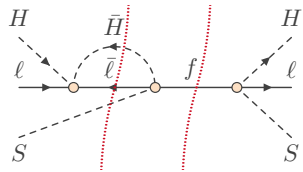






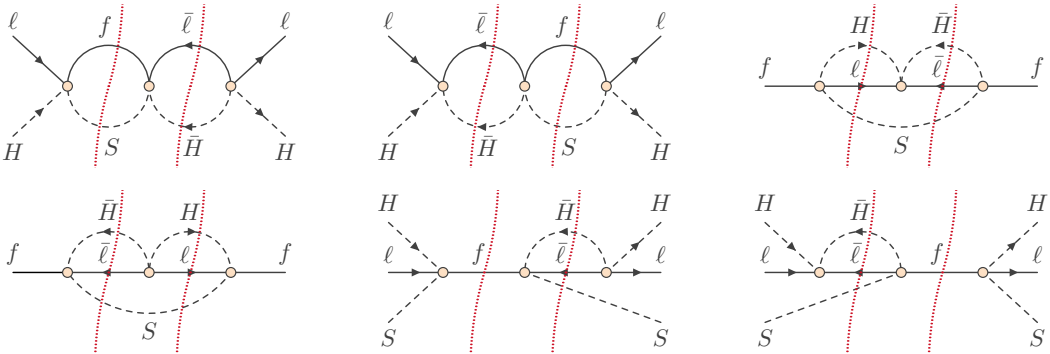






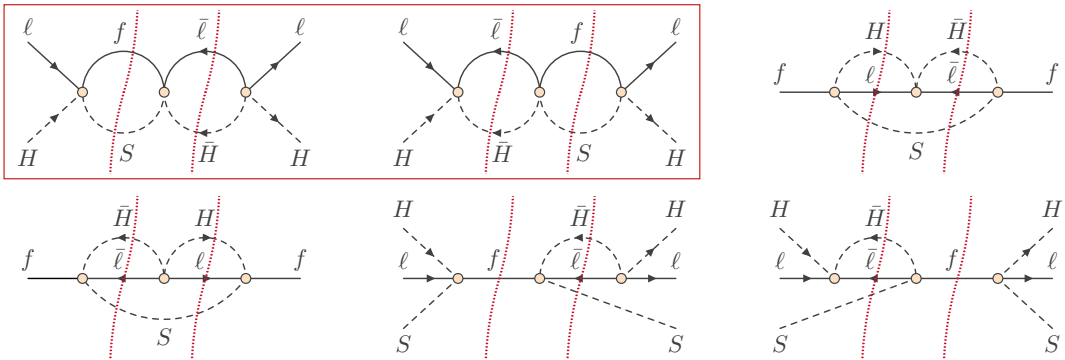
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$$\Delta\gamma^{\rm eq}_{i\to f} = \int \prod_{\forall i} [{\rm d}\boldsymbol{p}_i] \exp\{-E_i/T\} \int \prod_{\forall f} [{\rm d}\boldsymbol{p}_f] \frac{1}{V_4} \Delta |T_{fi}|^2 \tag{11}$$



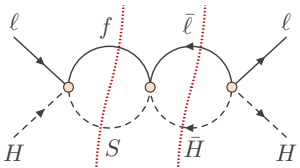
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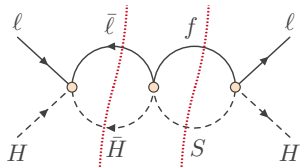
$$\Delta\gamma^{\rm eq}_{\ell H\to Sf} + \Delta\gamma^{\rm eq}_{\ell H\to \bar\ell\bar H} = 0 \tag{12}$$

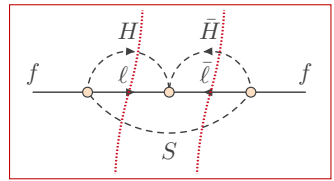


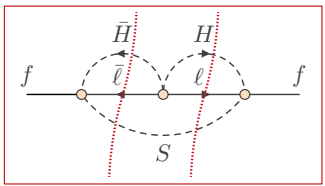
CP asymmetries in the minimal model

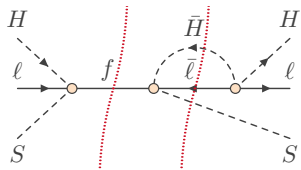
$$\Delta\gamma^{\rm eq}_{f\to\ell HS} + \Delta\gamma^{\rm eq}_{f\to\bar{\ell}\bar{H}S} = 0 \tag{13}$$

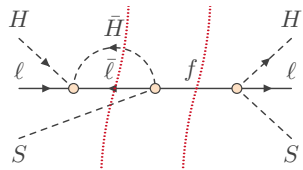






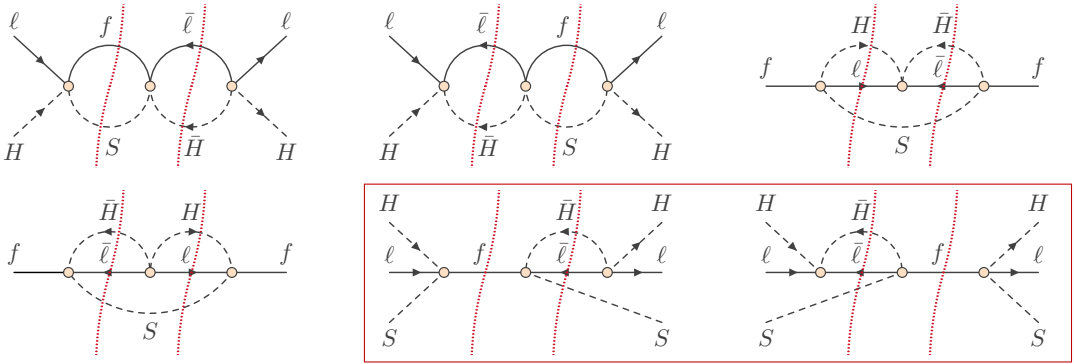






CP asymmetries in the minimal model

$$\Delta\gamma^{\rm eq}_{\ell HS\to f} + \Delta\gamma^{\rm eq}_{\ell HS\to \bar\ell\bar H S} = 0 \tag{14}$$



Boltzmann equations

$$sHz\frac{\mathrm{d}Y_f}{\mathrm{d}z} = \left(1 - \frac{Y_f}{Y_f^{\mathrm{eq}}}\frac{Y_S}{Y_S^{\mathrm{eq}}}\right)\gamma^{\mathrm{eq}}_{\ell H\to Sf} - \left(\frac{Y_f}{Y_f^{\mathrm{eq}}} - \frac{Y_S}{Y_S^{\mathrm{eq}}}\right)\left(\gamma^{\mathrm{eq}}_{fH\to S\bar{\ell}} + \gamma^{\mathrm{eq}}_{f\ell\to S\bar{H}}\right) \\ - \left(\frac{Y_f}{Y_f^{\mathrm{eq}}} - \frac{Y_S}{Y_S^{\mathrm{eq}}}\right)\left(\gamma^{\mathrm{eq}}_{f\to \ell HS} + \gamma^{\mathrm{eq}}_{f\to \bar{\ell}\bar{H}S}\right) \tag{15}$$

$$sHz\frac{\mathrm{d}Y_S}{\mathrm{d}z} = \left(1 - \frac{Y_f}{Y_f^{\mathrm{eq}}}\frac{Y_S}{Y_S^{\mathrm{eq}}}\right)\gamma^{\mathrm{eq}}_{\ell H\to Sf} + \left(\frac{Y_f}{Y_f^{\mathrm{eq}}} - \frac{Y_S}{Y_S^{\mathrm{eq}}}\right)\left(\gamma^{\mathrm{eq}}_{fH\to S\bar{\ell}} + \gamma^{\mathrm{eq}}_{f\ell\to S\bar{H}}\right) \\ + \left(\frac{Y_f}{Y_f^{\mathrm{eq}}} - \frac{Y_S}{Y_S^{\mathrm{eq}}}\right)\left(\gamma^{\mathrm{eq}}_{f\to \ell HS} + \gamma^{\mathrm{eq}}_{f\to \bar{\ell}\bar{H}S}\right) \tag{16}$$

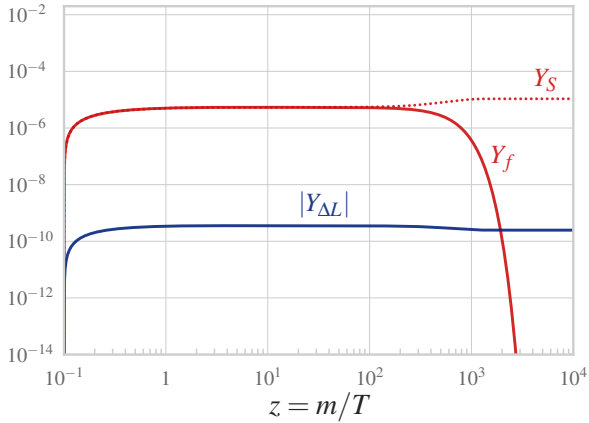
$$z = m/T$$

Boltzmann equations

$$
\begin{aligned}
sHz\frac{\mathrm{d}Y_{\Delta L}}{\mathrm{d}z} = &\left(1-\frac{Y_f}{Y_f^{\mathrm{eq}}}\frac{Y_S}{Y_S^{\mathrm{eq}}}\right)\Delta\gamma^{\mathrm{eq}}_{\ell H\to Sf}+\left(\frac{Y_f}{Y_f^{\mathrm{eq}}}-\frac{Y_S}{Y_S^{\mathrm{eq}}}\right)\Delta\gamma^{\mathrm{eq}}_{f\to\ell HS} \\
&-\frac{Y_{\Delta L}}{Y_\ell^{\mathrm{eq}}}\left(\frac{Y_f}{Y_f^{\mathrm{eq}}}+\frac{1}{3}\frac{Y_S}{Y_S^{\mathrm{eq}}}\right)\gamma^{\mathrm{eq}}_{f\bar{H}\to S\ell}-\frac{Y_{\Delta L}}{Y_\ell^{\mathrm{eq}}}\left(\frac{Y_S}{Y_S^{\mathrm{eq}}}+\frac{1}{3}\frac{Y_f}{Y_f^{\mathrm{eq}}}\right)\gamma^{\mathrm{eq}}_{S\bar{H}\to f\ell} \\
&-\frac{4}{3}\frac{Y_{\Delta L}}{Y_\ell^{\mathrm{eq}}}\left(\gamma^{\mathrm{eq}}_{Sf\to\ell H}+2\gamma^{\mathrm{eq}}_{\ell\bar{H}\to\ell H}+2\gamma^{\mathrm{eq}}_{H\bar{H}\to\ell\ell}+\frac{Y_S}{Y_S^{\mathrm{eq}}}\gamma^{\mathrm{eq}}_{f\to\ell HS}\right)
\end{aligned}
\tag{17}
$$

[Blažek, Maták, Ramaj, Sabová 2025]

Numerical analysis



$\Lambda = 10^{14}$ GeV, $T_{\rm R} = 5 \times 10^{12}$ GeV, $m = 5 \times 10^{11}$ GeV, $|\lambda|^2 = 1.8 \times 10^{-3}, \theta = 0.8$

Conclusions

- Holomorphic cutting rules are easy to use to derive full set of asymmetric reactions from a CP-odd basis invariant represented by a vacuum diagram.

- Minimal EFT explaining dark matter relic density, matter-antimatter asymmetry, and neutrino masses requires two $d = 5$ effective operators and two new particles.

Conclusions

- Holomorphic cutting rules are easy to use to derive full set of asymmetric reactions from a CP-odd basis invariant represented by a vacuum diagram.

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Thank you for your attention!

Backup

Ultraviolet freeze-in with $T \gg m$

$$\gamma^{\rm eq}_{\ell H \to Sf} + \gamma^{\rm eq}_{\bar{\ell}\bar{H} \to Sf} = \frac{|\lambda|^2}{8\pi^5}\frac{T^6}{\Lambda^2} = s(T_{\rm R})H(T_{\rm R}) \times S x^{-6} \tag{18}$$

$$\Delta\gamma^{\rm eq}_{\ell H \to Sf} = \frac{3\,{\rm Im}[\lambda^2\lambda'^*]}{32\pi^6}\frac{mT^6}{\Lambda^3} = s(T_{\rm R})H(T_{\rm R}) \times A x^{-6} \tag{19}$$

with $x = T_{\rm R}/T$

Ultraviolet freeze-in with $T \gg m$

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with $x = T_{\rm R}/T$

$$\underbrace{{\rm Im}[\lambda^2\lambda'^*] = \sum_{a,b}{\rm Im}[\lambda_a\lambda'^*_{ab}\lambda_b], \quad |\lambda|^2 = \sum_a|\lambda_a|^2, \quad |\lambda'|^2 = \sum_{a,b}|\lambda'_{ab}|^2}$$

$$\theta = -\frac{{\rm Im}[\lambda^2\lambda'^*]}{|\lambda|^2|\lambda'|}, \quad |\theta|\le 1, \quad m_\nu = \sqrt{\sum_a m^2_{\nu_a}} = \frac{v^2}{\Lambda}|\lambda'|$$

Ultraviolet freeze-in with $T \gg m$

$$\frac{\mathrm{d}Y_f}{\mathrm{d}x} = \frac{\mathrm{d}Y_S}{\mathrm{d}x} = Sx^{-2}, \quad \frac{\mathrm{d}Y_{\Delta L}}{\mathrm{d}x} = -\frac{\mathrm{d}Y_{\Delta(B-L)}}{\mathrm{d}x} = Ax^{-2} \tag{20}$$

1. Freeze-in at $T \lesssim T_{\mathrm{R}}$

$$Y_f \to S, \quad Y_S \to S, \quad Y_{\Delta(B-L)} \to -A$$

2. $f \to \ell HS, \bar{\ell}\bar{H}S$ asymmetric decays at $T \lesssim m$

$$Y_f \to 0, \quad Y_S \to 2S, \quad Y_{\Delta(B-L)} \to -\frac{3}{4}A$$

3. Sphalerons

$$Y_{\Delta B} = \frac{28}{79} Y_{\Delta(B-L)} = -\frac{21}{79} A$$

Ultraviolet freeze-in with $T \gg m$

$$\frac{\Omega_{b,0}}{\Omega_{c,0}} = \frac{Y_{\Delta B}}{Y_S}\frac{m_p}{m'} = \frac{63}{632}\frac{\theta}{\pi}\frac{m_p m_\nu}{v^2}\frac{m}{m'} \simeq 0.19 \tag{21}$$

For $m_\nu^2 \simeq |\Delta m_{32}^2| \simeq 2.5 \times 10^{-3}$ eV^2, we obtain $m/m' \gtrsim 10^{16}$.

[Navas *et al.* 2024 (Particle Data Group)]